RAMS microphysical parameterization - Meyers et al. (1997)

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Bulk microphysical schemes

- Represent hydrometeor size for each class with a distribution function such as a gamma type
- two moments of the distribution can be predicted - mixing ratio and number concentration, with mean diameter diagnosed
- In this scheme, the number concentration is prognosed for all hydrometeors but the cloud water

Categories of water

Vapor, cloud droplets, rain, pristine ice, snow, aggregates, graupel, and hail

- cloud droplets: liquid water, do not fall, formed from vapor
- rain: liquid water, large enough to fall
- pristine ice: formed from vapor, grows only by vapor deposition
- snow: relatively large ice crystals, grows by vapor deposition and riming

Categories of water, continued

- Aggregates: ice particles that have formed by collision and coalescence of pristine ice, snow, and/or other aggregates
- Graupel: approximately spherical in shape, formed by riming and/or partial melting of pristine ice, snow or aggregates. Graupel can carry up to only a low percentage of liquid. If the percentage grows, by either melting or riming, a graupel particle is re-categorized as hail.
- Hail: a high-density hydrometeor, considered spherical in shape. It is assumed to be formed by freezing of rain drops or by riming or partial melting of graupel. Hail is allowed to carry any fraction of liquid water up to, but not including, 100%, except that all but small hail will shed excessive liquid.

Gamma distribution

- Hydrometeors in each category are assumed to conform to a generalized gamma distribution

$$f_{gam}(D) = \frac{1}{\Gamma(\nu)}\left(\frac{D}{D_n}\right)^{\nu-1}\frac{1}{D_n}\exp\left(-\frac{D}{D_n}\right)$$

D = hydrometeor diameter

D_n = characteristic diameter

ν = shape parameter

Characteristic diameter

- Used to nondimensionalize D
- A diameter scaling factor for the distribution

$$D_{mean} = \int_0^\infty D f_{gam}(D)\,dD = \frac{\Gamma(\nu+1)}{\Gamma(\nu)} D_n = \nu D_n$$

Mass and terminal velocity

- Assumed that they can be expressed as power laws, based on empirical evidence

$$m = \alpha_m D^{\beta_m}$$

$$v_t = \alpha_{v_t} D^{\beta_{v_t}}$$

- The five parameters ν, α_m, β_m, α_{vt}, and β_{vt} are selected for each category based on available empirical data
- These parameters are held fixed in time and space for the duration of the simulation
- For the pristine ice and snow categories, multiple sets of these parameters are available, each describing a different crystal habit, and it is possible to switch during the simulation from one habit to another both spatially and temporally

Mixing ratio

- Determined using the concentration-normalized integral of the equation for mass

$$r = \frac{N_t}{\rho_a} \alpha_m D_n^{\beta_m} \frac{\Gamma(\nu + \beta m)}{\Gamma(\nu)}$$

- There are two free parameters from (r, N_t, D_n) to be determined for each category, the third parameter being obtained from the other two and the above equation

Continuity equations

$$\frac{\partial r}{\partial t} = ADV(r) + TURB(r) + SOURCE(r) + SEDIM(r)$$

$$\frac{\partial n}{\partial t} = ADV(n) + TURB(n) + SOURCE(n) + SEDIM(n)$$

$$r = [r_r, r_p, r_s, r_a, r_g, r_h, r_t]$$

$$n = [n_r, n_p, n_s, n_a, n_g, n_h]$$

The sum of the mixing ratios of cloud and vapor is determined as a difference of the prognostic mixing ratios

$$r_{c+v} = r_t - (r_r + r_p + r_s + r_a + r_g + r_h)$$

$$r_c = \max[\,0, r_{c+v} - r_{sl}\,] \qquad r_{sl} = \frac{0.622 e_{sl}}{p - e_{sl}}$$

$$T_a = \theta_{il}\left(\frac{p}{p_{oo}}\right)^{R/C_p}\left[1 + \frac{Q_{lat}}{C_p \max(T_a, 253)}\right]$$

$$Q_{lat} = [r_r + r_c + (1 - i_g) r_g + (1 - i_h) r_h] L_{lv} + (r_p + r_s + r_a + i_g r_g + i_h r_h) L_{iv}$$

e_{sl} is the saturation vapor pressure evaluated from an 8th order polynomial in air temperature

Q_{lat} is the energy per unit condensate mass required to evaporate and/or sublimate at constant temperature all condensate mass

i_g and i_h are the fractional amounts of ice in the graupel and hail categories

Hydrometeor heat budget

A heat budget equation is formulated for each category to compute representative hydrometeor temperatures

$$Q^{t+\Delta t} = (\dot{Q}_{vd} + \dot{Q}_{hd})\Delta t + Q^{*}$$

The heat and vapor diffusion terms are very sensitive to temperature and would necessitate the use of a very small time step for stable integration

A practical means for obtaining a stable category temperature is to solve the diffusion and time dependent terms implicitly by expressing them as a function of temperature at time t+Δt

$$Q^{t+\Delta t} = C\left\{ BL\rho_a \psi \left[r_v - r_{vs0} - \left(\frac{dr_{vsh}}{dT} \right)_0 (T_c - T_0) \right] + \kappa (T_{ac} - T_c) \right\} + Q^*$$

$$C = \frac{2\pi F_{\mathrm{Re}} N_t \Delta t}{\rho_a r} \qquad B = \frac{1}{1 + N_t 2\pi \psi F_{\mathrm{Re}} \Delta t}$$

$$F_{\mathrm{Re}} \equiv \int_0^\infty D f_{\mathrm{Re}} f_{gam}(D) dD \qquad f_{\mathrm{Re}} = \left[1.0 + 0.229 \left(\frac{v_t D}{V_k} \right)^{0.5} \right] S$$

L = latent heat ; ρ = density of air ; ψ = vapor diffusivity ; r_v = mass mixing ratio of water vapor

r_{vs0} = reference value of saturation mixing ratio

r_{vsh} = saturation mixing ratio at hydrometeor surface

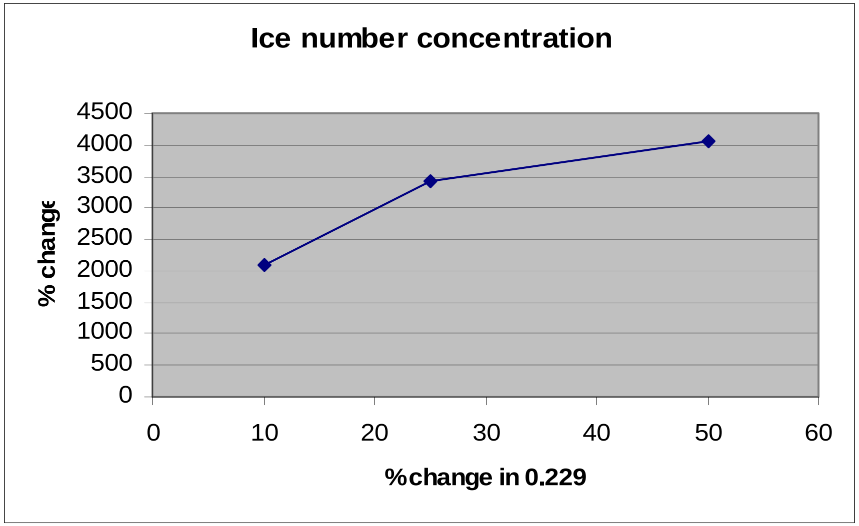
T_c = mean temperature of a category ; T_0 = reference temperature ; T_{ac} = air temperature

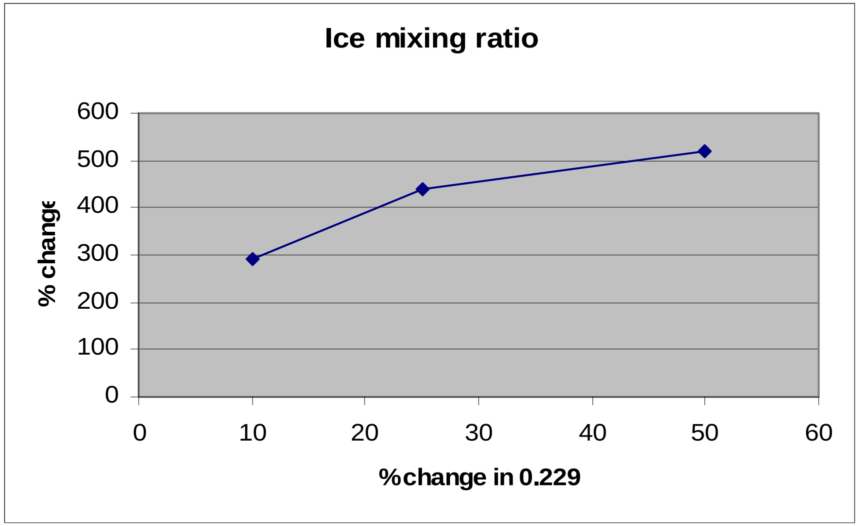
κ = thermal conductivity of air ; Q* = value of Q before heat and vapor diffusion

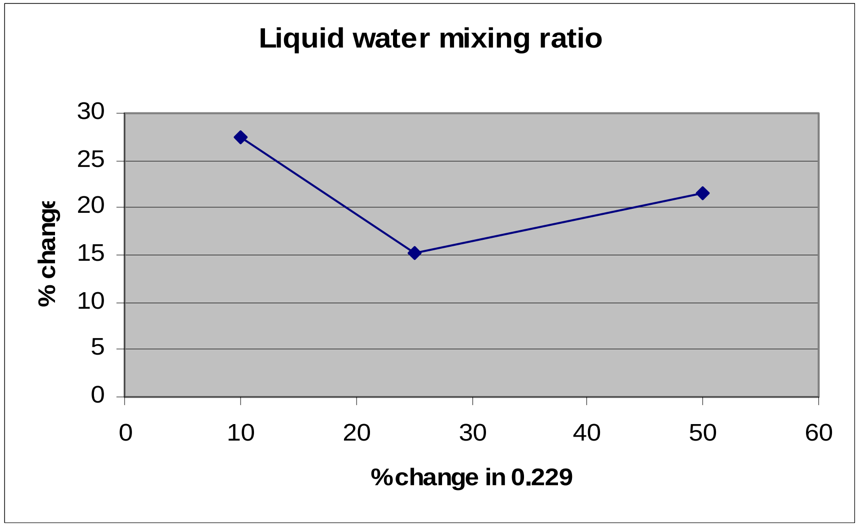
V_k = kinematic viscosity of air

- The derivation of the equation for Q^{t+dt} uses two empirically derived formulas with three tunable constants, two of which appear in both the numerator and denominator
- This equation describes temperature of the category, as well as the fraction of liquid present.
- These temperatures govern the vapor diffusion rates

$$f_{\mathrm{Re}} = \left[1.0 - 0.229 \left(\frac{v_t D}{V_k} \right)^{0.5} \right] S$$







Ice nucleation

- Deposition nucleation - vapor molecules attach to an IN
- Condensation-freezing nucleation - vapor molecules attach as liquid, then freeze
- Contact freezing nucleation - occurs when an IN comes into contact with an existing supercooled cloud water droplet
- Homogeneous nucleation - a small group of water molecules take on a crystal lattice structure due to random motions

Deposition and Condensation-freezing nucleation

$$(N_t)_d = \exp(6.269 + 12.96 r_{si})$$

r_{si}= supersaturation with respect to ice

$(N_t)_d$ = total number of crystals per m^3 that can nucleate under the given environmental conditions

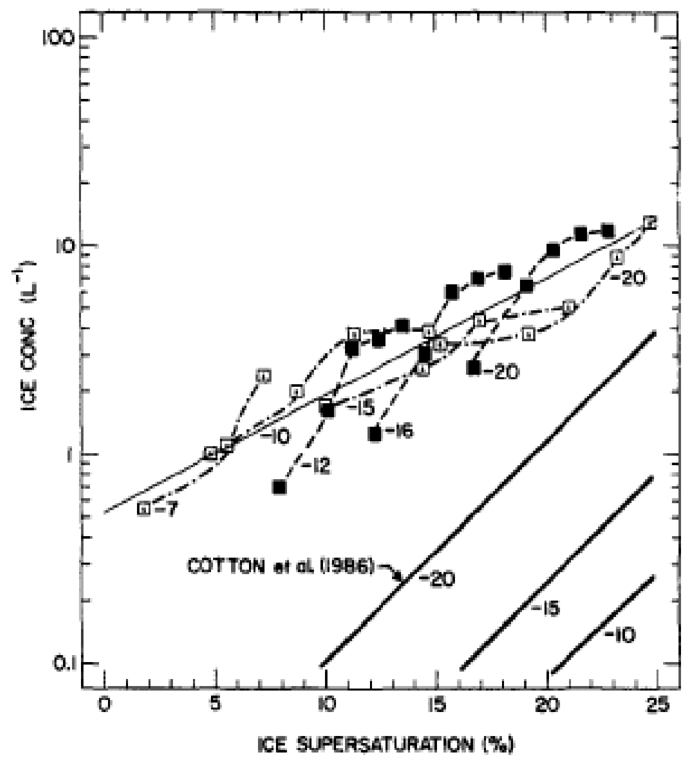
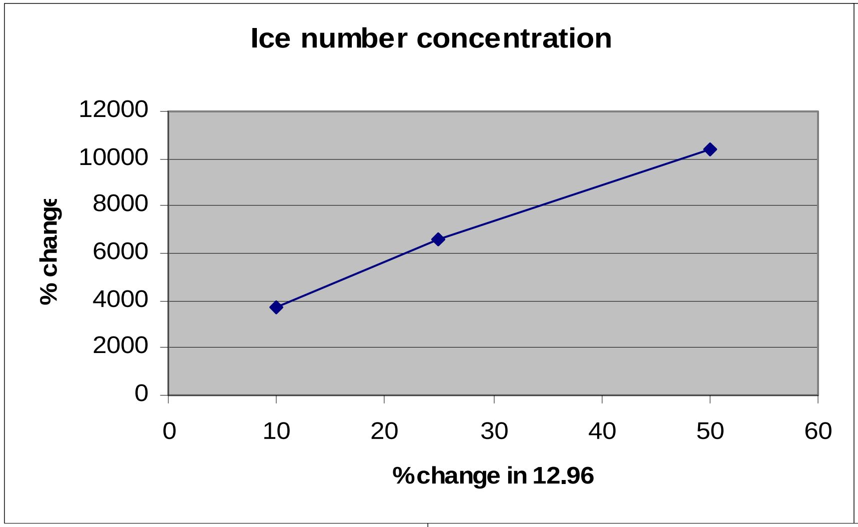
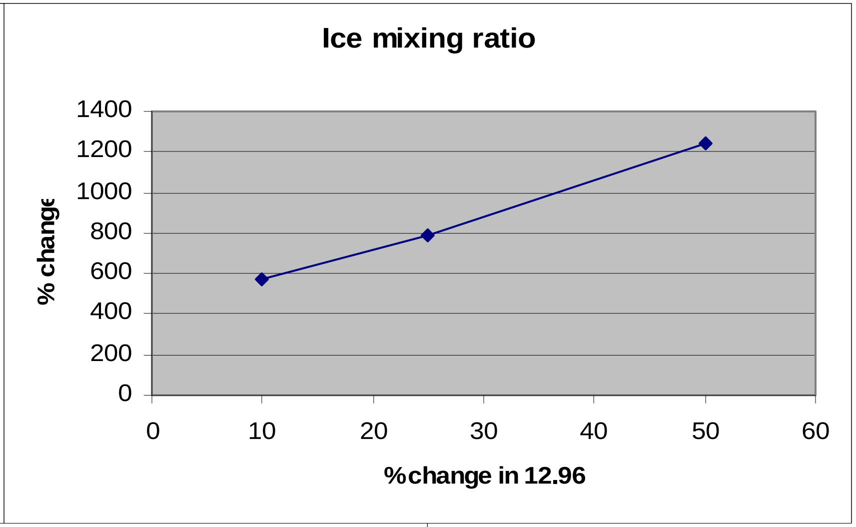
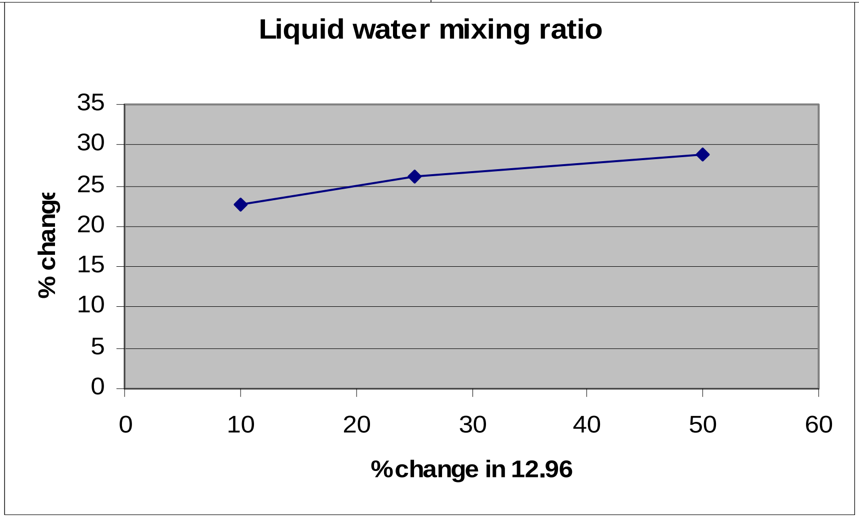


FIG. 3. Continuous-flow diffusion-chamber ice-nucleus concentration measurements versus ice supersaturation from (open square) Rogers (1982), and from (filled square) Al-Naimi and Saunders (1985). Constant-temperature measurement series are indicated and the regression given in (2.4) is shown. Also presented are constant temperature values predicted by the deposition–condensation-freezing nucleation model formulated by Cotton et al. (1986).

$$(N_t)_d = \exp(6.269 + 12.96 r_{si})$$







Contact freezing

Transport of the IN to the droplet results from:

- diffusiophoresis - net vapor mass flux toward a droplet growing by condensation
- thermophoresis - a flux of aerosols toward the droplet resulting from the gradient of temperature when the droplet is evaporatively cooled below the environmental temperature
- Brownian motion - random transport of aerosols due to collisions with air molecules

$$\left(\frac{dN_t}{dt}\right)_v = F_1 F_2 \frac{R_v T_a}{L_{lv}\rho_a}$$ diffusiophoresis

$$\left(\frac{dN_t}{dt}\right)_t = \frac{F_1 F_2 f_t}{\rho_a}$$ thermophoresis

$$\left(\frac{dN_t}{dt}\right)_b = F_1 \psi_a$$ Brownian motion

$$F_1 = 2\pi D_c N_{tc} N_a$$

$$F_2 = \frac{\kappa}{p}(T_a - T_c)$$

$$f_t = \frac{0.4[1 + 1.45K_n + 0.4K_n \exp(-1/K_n)](\kappa + 2.5K_n\kappa_a)}{(1+3K_n)(2\kappa + 5\kappa_a K_n + \kappa_a)}$$

$$N_a = \exp(4.22 - 0.262T_c)$$ The number of IN per m^3 available for contact freezing

Homogeneous nucleation

$$(N_t)_c = N_t \int_0^{\infty} \left[1 - \exp\left(-10^{\phi} \frac{\pi D^3}{6} n(D) \right) \right] dD$$

$$\phi = -606.3952 - 52.6611 T_c - 1.7439 T_c^2 - 0.0265 T_c^3 - 0.0001536 T_c^4$$

This formula is for activated cloud droplets where the solute and curvature effects are negligible, applied in the temperature range -50°C<T_c< -30°C. At colder temperatures, the value at -50°C is applied (nucleation of all cloud droplets)

The integral is precomputed and a table of values compiled for computational efficiency

Total effect of all ice nucleation processes

$$\Delta N_t = (N_t)_d + (N_t)_c + (N_t)_h + \left[\left(\frac{dN_t}{dt} \right)_v + \left(\frac{dN_t}{dt} \right)_t + \left(\frac{dN_t}{dt} \right)_b \right] \Delta t$$

$$\Delta r_p = \Delta N_t m_n / \rho_a$$

m_n=assumed initial mass of a nucleated particle

Collision and Coalescence

$$\frac{dr_x}{dt} = \frac{N_{tx} N_{ty} \pi F_\rho}{4\rho_a} \int_0^\infty \int_0^\infty m(D_x)(D_x + D_y)^2 \,|\, v_{tx}(D_x) - v_{ty}(D_y) \,|\, f_{gamx}(D_x) f_{gamy}(D_y) E(x,y) dD_x dD_y$$

$$\frac{dN_{tx}}{dt} = -\frac{N_{tx} N_{ty} \pi F_\rho}{4} \int_0^\infty \int_0^\infty (D_x + D_y)^2 \,|\, v_{tx}(D_x) - v_{ty}(D_y) \,|\, f_{gamx}(D_x) f_{gamy}(D_y) E(x,y) dD_x dD_y$$

- Solutions to these integrals are pre-computed and tabulated in 3-D look-up tables
- Values are interpolated from the table bi-linearly

Collisions between liquid and liquid or ice and ice

Table 2
Categories

Collected category	Collecting category	Destination category
cloud water	rain	rain
pristine ice	pristine ice	aggregates
pristine ice	snow	aggregates
snow	pristine ice	aggregates
pristine ice	aggregates	aggregates
pristine ice	graupel	graupel
pristine ice	hail	hail
snow	snow	aggregates
snow	aggregates	aggregates
snow	graupel	graupel
snow	hail	hail
aggregates	graupel	graupel
aggregates	hail	hail
graupel	hail	hail

From Walko et al, 1995

Ice-liquid interactions

- The destination of the collection is determined by
  - the type and amount of colliding ice hydrometeor
  - the amount of rain or cloud mixing ratio being collected
  - the diagnosed liquid and ice contents of the species produced by the collection event after the constituents have reached thermal equilibrium
- The amounts of mixing ratio, number concentration, and thermal energy produced by the collisions are divided between the input ice category and the destination ice category

$$r_{\sec} = \min(r_{colt}, \zeta r_{liq} + \chi r_{coll})$$

$$n_{conv} = \max(0., (r_{colt} - r_{ret}) / r_{colt}) \times n_{colt})$$

r_{sec} = amount of mass being sent to the secondary ice category

r_{colt} = amount of collected mass

r_{liq} = mixing ratio of the liquid portion of the coalesced hydrometeor after the two contributors reach thermal equilibrium

r_{coll} = amount of collected mass of the liquid categories

n_{conv} = number concentration tendency that is converted to the third hydrometeor category

The weighting factors determine the transfer during collection of liquid based on the hydrometeors involved. The remaining content of the coalesced hydrometeor is retained in the input ice category

Autoconversion - transition from cloud droplets to rain drops

Characteristic water content

$$L = 2.7 \times 10^{-2} r_c \left(\tfrac{1}{16} \times 10^{20} D_m^4 (1+\nu)^{-0.5} - 0.4\right)$$

Characteristic time scale

$$\tau = \frac{3.7}{r_c \rho} \left(0.5 \times 10^6 D_m (1+\nu)^{-0.5} - 0.75\right)^{-1}$$

Mixing ratio tendency

$$\frac{dr_r}{dt} = \frac{\rho_w L}{\rho \tau}$$

Number concentration tendency

$$\frac{dn_r}{dt} = 3.5 \times 10^6 \frac{L}{\tau}$$

Collisional breakup

Assumes that filament breakup is the only active mode

$$E_c(D_m) = \begin{cases} 1 & \text{For } D_m < D_{cut} \\ 2 - \exp[A(D_m - D_{cut})] & D_m > D_{cut} \end{cases}$$

A=2300

D_m = mean diameter

D_{cut} = 600 μm

Deposition and Evaporation

- All hydrometeors are assumed to grow by deposition and maintain their identity in a saturated environment
- During conditions of ice supersaturation, pristine ice number concentration and mass mixing ratio are transferred to the snow category by vapor depositional growth
- The mean size of the pristine ice crystals are bounded by their size, set to 120 μm

Melting and Shedding

- At this stage in the sequence of computations, the sources and sinks of mass and energy from all other processes have been summed, and any melting is diagnosed as resulting from an energy surplus
- It is assumed that the snow and aggregate categories lose all melted mass during the melting process, which is converted to the graupel category along with an equal amount of ice mass from the snow or aggregate category.
- Once the fraction of water in graupel reaches 30% the graupel spectrum is assumed to be transformed into a high density hail category

- The melting and shedding of hail is handled simultaneously in a look-up table to avoid over-depletion by these two processes if handled separately
- An expression for the critical mass of water on the ice-core's surface before shedding occurs:

$$M_{Wcrit}(D) = 0.268 \times 10^{-3} + 0.1389 m_i$$

- It is assumed that the melting process is responsible for all liquid water accretion and that all melted water is available for shedding
- The mixing ratio of the mass shed by the ice spheres is calculated, and the number of raindrops shed is determined by assuming that the shed size is D=0.001 m

Sedimentation

- Sedimentation only deals with the mass-weighted relative fall velocity between the hydrometeor class and air
- The conservation equations are evaluated without the sedimentation terms, then sedimentation is carried out on the updated mixing ratios and number concentrations
- A Lagrangian scheme is used to transport the mixing ratio from any given grid cell to a lower height in the vertical column
- It is assumed that number concentration is transported in the same proportion as mixing ratio to ensure that the mixing ratio and number concentrations do not fall into separate grid volumes

Equation closure

- The model may predict number concentrations and mixing ratios that are inconsistent with each other, resulting in the diagnosis of extreme hydrometeor diameters
- This is most likely along sharp boundaries of the cloud or precipitation shafts
- If the diagnosed diameter is not within prescribed bounds, the concentration is re-diagnosed based on the limiting diameter

Table 4
Diameter bounds for each of the hydrometeors with $D_{n\min}$ and $D_{n\max}$

Hydrometeor	$D_{n\min}$ (m)	$D_{n\max}$ (m)
cloud droplets	1.0e-6	4.0e-5
rain	4.0e-5	0.01
pristine ice crystals	1.0e-6	1.2e-4
snow	1.2e-4	0.01
aggregates	1.0e-6	0.01
graupel	1.0e-6	0.005
hail	1.0e-6	0.01

From Meyers et al (1997)

Sensitivity Studies

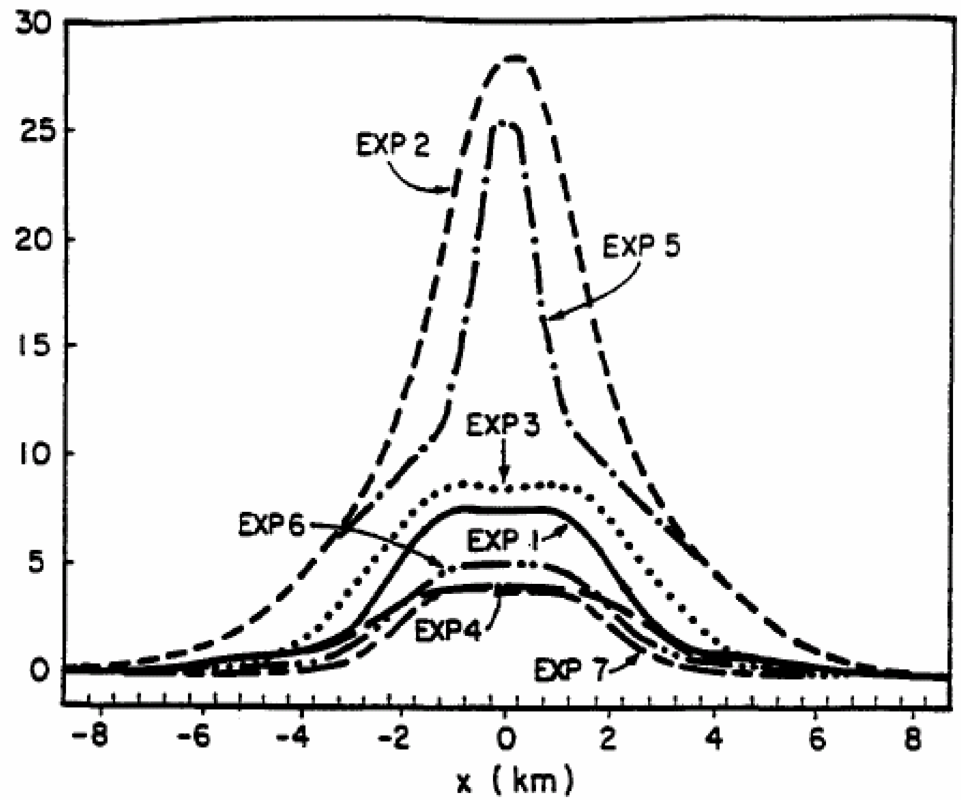


Fig. 9. Accumulated precipitation after 30 minutes for each of the sensitivity runs. Units are in mm.

Table 5
Sensitivity tests and setup

Experiment	Moments	ν	N_c	Crystal habit
EXP1	2	1	300 cm^{-3}	hexagonal plates
EXP2	1 except for PI	1	300 cm^{-3}	hexagonal plates
EXP3	2	1	60 cm^{-3}	hexagonal plates
EXP4	2	1	1500 cm^{-3}	hexagonal plates
EXP5	2	3	300 cm^{-3}	hexagonal plates
EXP6	2	1	300 cm^{-3}	variable habits
EXP7	2	1	300 cm^{-3}	variable habit with vertical dependence

Summary

- About 38 tunable constants
- Sensitivity tests show the parameterization is quite sensitive to cloud droplet concentrations, ice crystal habit, as well as the shape of the size distribution

Look-up Table

- Due to the complexity of this parameterization, implementing it as one big look-up table would be rather difficult
- It would be more simple (although less efficient) to implement each process as a look-up table and then sum up the results to see the net change with each time step